PROGRESS IN THE DEVELOPMENT OF A SIMPLE, LASER-PUMPED, VAPOR-CELL CLOCK

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Abstract

We are developing a laser-pumped Rb clock with the primary goals of keeping the clock design simple and compact, with low power consumption. We employ a VCSEL diode laser, forcing us to deal with a large PM-to-AM noise conversion problem, and we employ a single cell to lock both the laser wavelength and the VCXO clock frequency. Consequently, we must stabilize the laser using linear absorption spectroscopy, rather than sub-Doppler techniques. Here, we discuss the present status of our laser-pumped clock and our future plans.

INTRODUCTION

In the laser-pumped vapor-cell clock, a diode laser replaces the rf-discharge lamp and the isotopic filter cell of the traditional Rb clock. This device's advantages include its simplicity of design, its reasonably well-understood physics, and the opportunity to develop clocks based on Cs as well as Rb. Belying the uncomplicated design, however, are a number of challenges: laser phase-noise (PM) to amplitude-noise (AM) conversion can play a major role in limiting the device's signal-to-noise ratio**[1-3]**; the laser wavelength must be actively stabilized against long-term drift, and depending on how laser stabilization is accomplished the light-shift can transform laser wavelength instability into clock frequency instability **[4,5]**. Surmounting these challenges can require the use of narrow linewidth lasers and a 2nd cell for sub-Doppler spectroscopy **[6]**.

We are developing a laser-pumped Rb clock with the primary goal of keeping the clock design simple, compact, and low power: we use relatively broad linewidth VCSELs ($\Delta\nu \sim 50$ to 100 MHz) and a single resonance cell **[7]**. Consequently, we must deal with the potential for significant laser PM-to-AM noise conversion; we must employ linear absorption spectroscopy for laser wavelength stabilization, and we must deal with a potential light-shift problem as a consequence of non-ideal laser-locking conditions. Here, we review the choices we have made to overcome some of these problems, and we present our clock's frequency stability to date.

OUR DESIGN APPROACH: ADVANTAGES AND DISADVANTAGES

To overcome the problem of laser PM-to-AM noise conversion, without resorting to narrow linewidth lasers, we pressure broaden the Rb optical absorption line with $P_{\text{buffer-gas}} \cong 100$ torr, which yields a measured optical absorption linewidth in our clock (FWHM) of 1.8 GHz. The down-side of working at high buffer-gas pressure is that we have a relatively large temperature coefficient **[8]**. Therefore, balancing our mixed Ar/N_2 buffer gas ratio, and working at the optimum cell temperature, is very important.

An additional advantage to high buffer-gas pressure, however, is that it reduces the light-shift coefficient **[4]**. In our design, shifts in the laser wavelength due (for example) to laser temperature variations are corrected by adjusting the laser's injection current **[9]**. However, the injection current controls the light intensity, so that if the clock suffers a non-zero light shift then laser temperature variations will be mapped onto the clock's output frequency. Reducing the light-shift coefficient and working at the lowest possible light intensities can mitigate this effect.

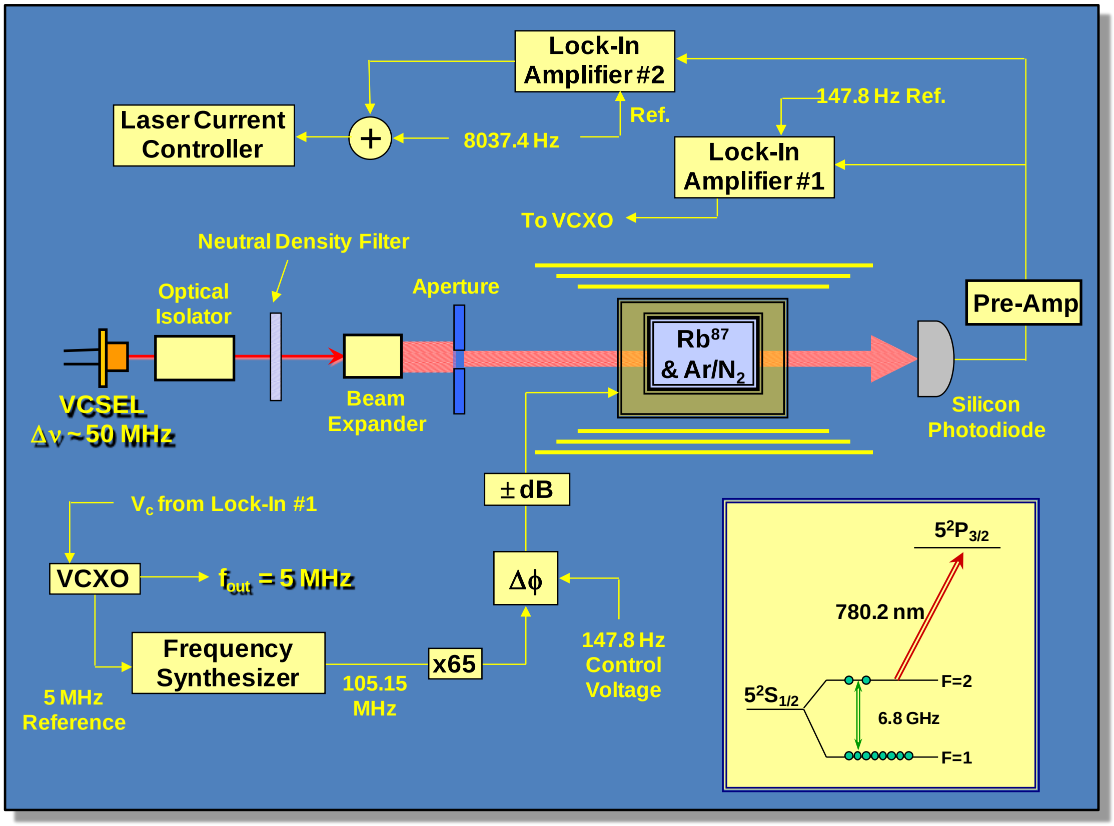

Figure 1. Block diagram of our "simple design," laser-pumped, vapor-cell atomic clock. Essentially, a VCSEL diode laser replaces the lamp and filter cell of the conventional *lamp*-pumped vapor-cell clock.

THE LASER-PUMPED RB CLOCK

A functional block diagram of our clock is presented in Figure 1. Due to its very low threshold current, we employ a VCSEL diode laser for optical pumping (i.e., Vertical Cavity Surface Emitting Laser) **[10]**. The laser light passes through a neutral density filter to lower its intensity, thereby minimizing the clock's light shift, and is then expanded. The expanded beam is apertured, producing a nearly "top hat" intensity profile, before it enters our cylindrical Pyrex resonance cell containing 55 torr of N_2 and 40 torr of Ar (cell length = 3.9 cm and cell diameter = 2.2 cm). The resonance cell is housed in a TE_{011} microwave cavity, which in turn is contained in a solenoid that produces a magnetic field of 140 mG. The cavity and solenoid sit inside three cylindrical μ-metal shields, and the transmitted light intensity is detected with a Si photodiode. The resonance cell is heated with braided windings wrapped around the microwave cavity, and the resonance cell is maintained at a temperature of 30 ^{o}C. At this temperature the vapor's optical depth is 6.5 cm, which was determined through measurement. (The reason for our clock's low resonance-cell temperature will be discussed subsequently.)

The laser is tuned to the $5^2S_{1/2}(F_g=2) - 5^2P_{3/2}$ transition at 780 nm, and is locked to this resonance using linear absorption spectroscopy: we modulate the laser injection current (i.e., wavelength) at ~ 8 kHz, and the amplitude of the transmitted light-intensity signal at 8 kHz is fed back to the injection current as a wavelength correction **[11]**. The microwave frequency at 6.8 GHz is also modulated, but at the lower frequency of 148 Hz. The amplitude of the transmitted light-intensity signal at 148 Hz is fed back to a voltage-controlled crystal oscillator (VCXO) as a correction signal, thereby locking the VCXO's output frequency to the ^{87}Rb 0-0 ground-state hyperfine transition. The stabilized VCXO is our 5 MHz clock frequency, and also provides a reference for our low phase noise microwave synthesizer.

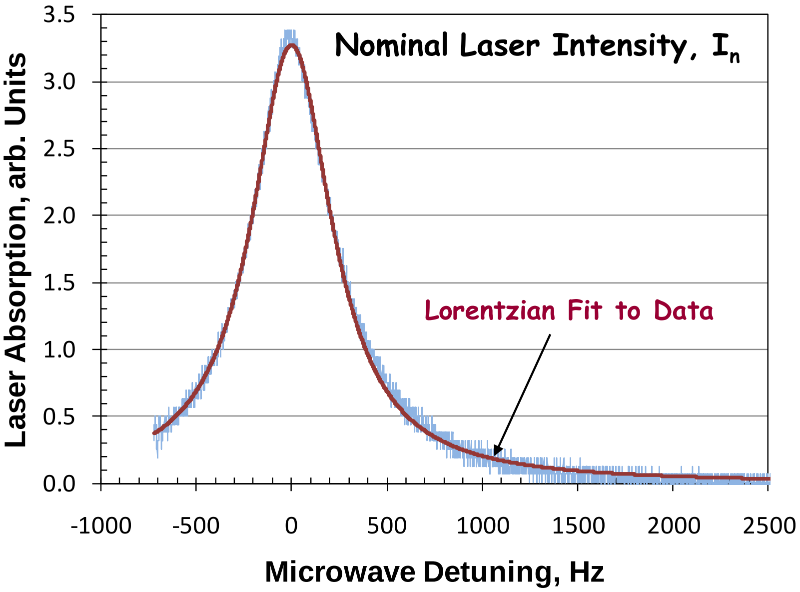

Figure 2. ^{87}Rb 0-0 hyperfine transition as observed in the transmitted light intensity at our nominal laser intensity: ND = 1.0. For these measurements the photodiode amplification was set too low: the fluctuations in the data are not noise, but are simply quantization errors.

Figure 2 is an example of our 0-0 transition clock lineshape taken at our nominal laser intensity (set by an ND = 1.0 filter). At the present stage of our experiments, we have not yet calibrated the VCSEL laser intensity incident on the vapor cell, nor have we measured our signal-to-noise ratio. (We plan to do this in the not too distant future, after we have more fully investigated our optimum operating conditions, i.e., light intensity, microwave power, cell temperature, etc.) The solid line through the data is a least squares fit to a Lorentzian lineshape, which yields a HWHM of 258 Hz. Extrapolating the linewidth to zero microwave power, the residual HWHM at this light intensity was 75 Hz, which reflects contributions from optical pumping, diffusion to the resonance cell walls, and Rb/N_2 along with Rb/Ar dephasing collisions.

In our preliminary investigations, we measured the clock's sensitivity to various perturbations. For microwave power, we found that $dy/dP \cong -2\times10^{-12}$/dB. Though this sensitivity may represent a pathway by which very slow changes in cavity Q could affect the clock frequency **[12]**, it is likely too small to affect the clock's Allan deviation at averaging times of 10^3 – 10^4 seconds: to affect the clock frequency at the 10^{-14} level, the microwave power would have to vary by 0.1% over an hour, and this seems large for such a "short" timescale. Additionally, at out nominal laser intensity we found that $dy/dI_{Laser} \sim 3\times10^{-12}$/%. Investigations suggested that at this nominal level laser intensity variations were affecting our medium-term Allan deviation. Consequently, we now operate the clock with an ND = 1.6 filter, which reduces the light-shift coefficient to about 1×10^{-12}/%. Further experiments are planned to better quantify the effect of light intensity variations on our clock's performance. Finally, $dy/dT_{cell} \cong -7\times10^{-10}/^{o}C$, suggesting that our clock may be sensitive to environmental temperature fluctuations: to reach an Allan deviation of 10^{-13}, resonance-cell temperature fluctuations need to be less than 200 μK.

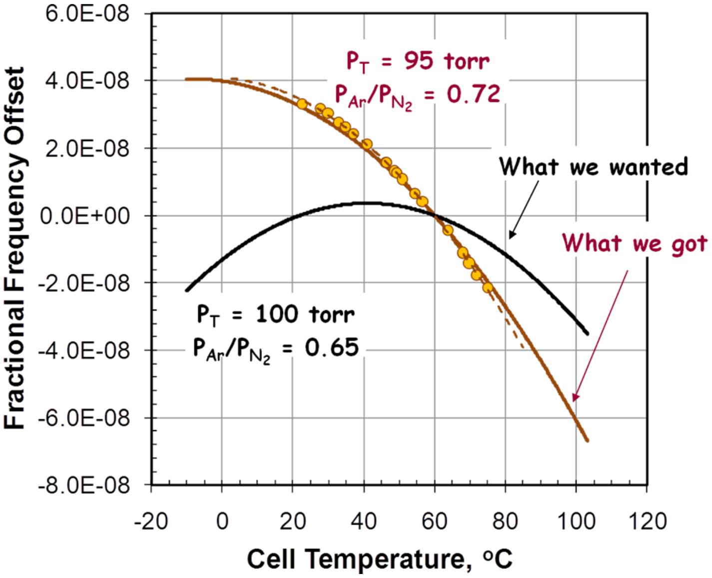

Figure 3. Temperature sensitivity of our vapor-cell clock. Due to a misunderstanding with the resonance cell manufacturer, we received a resonance cell with a non-ideal mixture of N_2 and Ar; another cell has been ordered.

As is well known, the frequency of a vapor-cell clock has a quadratic dependence on temperature **[8]**, and the temperature of the extremum (i.e., $dy/dT_{cell} = 0$) is a function of the partial pressures for a mixed buffer-gas system. As illustrated in Figure 3, we had originally planned for our mixed buffer-gas system to give us an extremum in $y(T_{cell})$ somewhere between 35 °C and 45 °C (i.e., $P_{Ar}/P_{N_2} = 0.65$). Our thinking was that a temperature around 40 °C would give us a reasonable optical depth (in a 100 torr cell) for a good signal-to-noise ratio, while at the same time guaranteeing $dy/dT_{cell} \cong 0$. Unfortunately, the cell manufacturer did not realize the critical nature of our partial pressures, and so we received a sub-optimal cell: $P_{Ar}/P_{N_2} = 0.72$. The extremum of $y(T_{cell})$ for this buffer gas mixture occurs near 0 °C, and so we have chosen T_{cell} = 30 °C as our best compromise for good signal-to-noise and low temperature sensitivity. Another resonance cell has been ordered.

ALLAN DEVIATION

Figure 4 shows the Allan deviation of our simple-design, laser-pumped Rb clock along with several other clocks. The laser-pumped clock results of Lewis & Feldman **[13]** and Chantry *et al*. **[14]** were with designs similar to ours (i.e., a single cell for laser and microwave frequency locking and broad linewidth lasers), though the resonance cell dimensions were different. For comparison, the figure also shows a high-quality, *lamp*-pumped Rb clock's performance. Until very recently, our short-term stability was limited by noise in our proportional-controller feedback loop, though we now believe we may be at the shot-noise limit. Our long-term stability is likely limited by vapor-cell temperature fluctuations (~ ±0.5 mK over 30 minutes). These hypotheses regarding the short and long-term stability of the clock need to be verified. Nevertheless, it is clear that excellent short-term frequency stability can be achieved in a laser-pumped, vapor-cell clock of very simple design. Further, if temperature fluctuations truly are the source of our long-term frequency instability, then a more ideal ratio of buffer-gas partial pressures should result in a clock with improved medium and long-term performance.

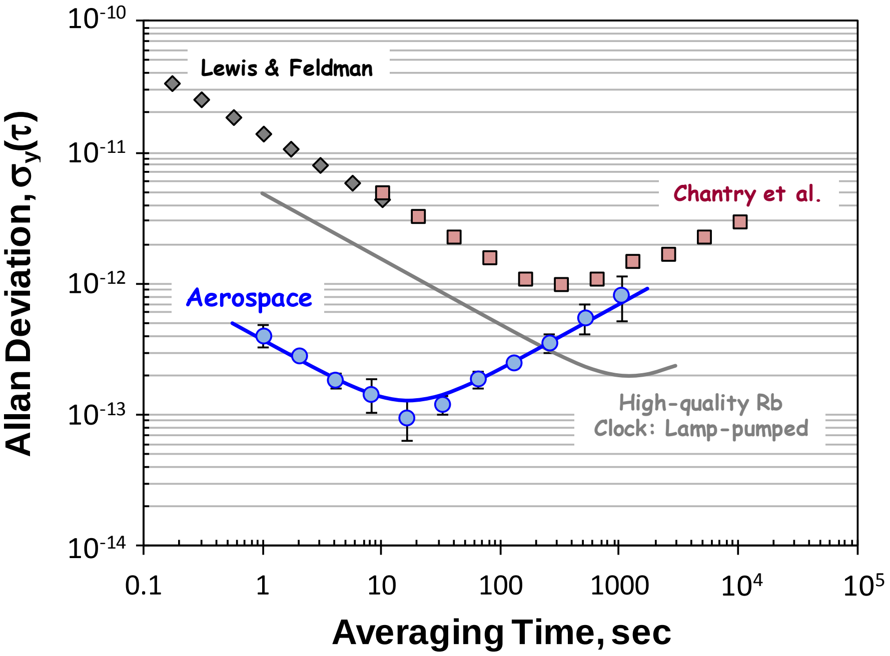

Figure 4. Allan deviation of our simple-design, laser-pumped Rb clock at present (circles), along with two other simple-design, laser-pumped, vapor-cell clocks. The solitary solid line shows the performance of a high-quality *lamp*-pumped Rb clock.

CONCLUSION

Here, we have summarized our progress in developing a laser-pumped vapor-cell clock of simple design. The design simplicity comes from our use of a single resonance cell for both laser and microwave frequency stabilization, and our use of a broad linewidth VCSEL diode laser. As a result of our design choices, we have had to carefully consider laser PM-to-AM conversion and the light-shift effect. The present work shows that it is possible to deal with these issues and achieve a frequency stability ~ 10^{-13} in 10 seconds of averaging. Our future work will focus on verifying shot-noise limited performance, possibly improving the shot-noise limit by working at shorter optical depths and/or higher laser intensities, and improving the long-term stability.

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